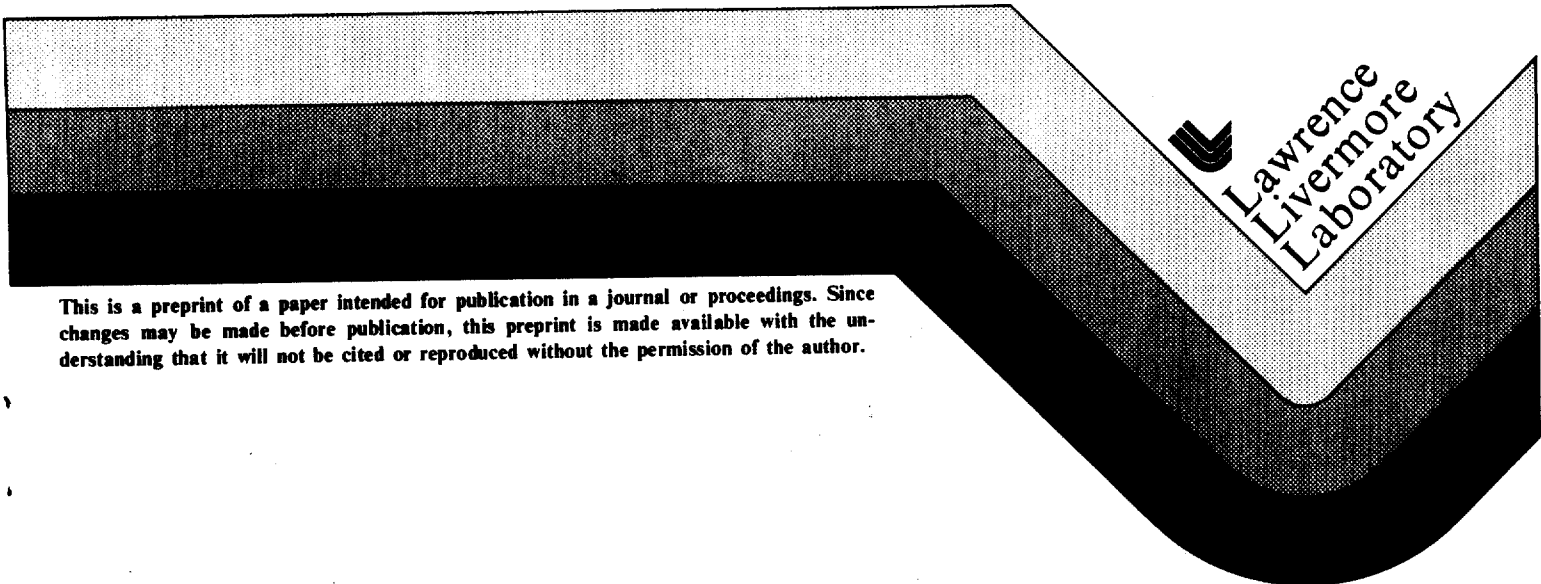


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This paper was prepared for submittal to the  
Proceedings of the 1980 Applied Superconductivity Conference  
Santa Fe, New Mexico  
September 29 - October 2, 1980

September 22, 1980



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# BACKGROUND FIELD COILS FOR THE HIGH FIELD TEST FACILITY\*

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## Abstract

The High Field Test Facility (HFTF), presently under construction at LLNL, is a set of superconducting coils that will be used to test 1-m-o.d. coils of prototype conductors for fusion magnets in fields up to 12 T. The facility consists of two concentric sets of coils; the outer set is a stack of Nb-Ti solenoids, and the inner set is a pair of solenoids made of cryogenically-stabilized, multifilamentary Nb<sub>3</sub>Sn superconductor, developed for use in mirror-fusion magnets. The HFTF system is designed to be parted along the midplane to allow high-field conductors, under development for Tokamak fusion machines, to be inserted and tested. The background field coils were wound pancake-fashion, with cold-welded joints at both the inner and outer diameters. Turn-to-turn insulation was fabricated at LLNL from epoxy-fiberglass strip. The coils were assembled and tested in our 2-m-diam cryostat to verify their operation.

## Introduction

The coils for the High Field Test Facility (HFTF), presently under construction at LLNL, consist of a split pair of multifilamentary Nb<sub>3</sub>Sn coils inside a set of Nb-Ti coils. This facility was originally designed to test Nb<sub>3</sub>Sn conductor that was being developed for mirror-fusion magnets and was redesigned to allow coils produced in the 12 T Test Coil Program to be tested. Figure 1 shows a half section of the HFTF coil system with the facility Nb<sub>3</sub>Sn coils split and a 12 T insert test coil in position. Table 1 presents parameters of the various HFTF coils. An overview of the development work on the HFTF has been presented elsewhere.<sup>1</sup> In this paper, we present details of the Nb-Ti background coils.

## Coil Construction

The background coils were wound pancake-fashion. The smaller coils, used to provide a backing field for the MFTF Test Coil,<sup>2</sup> were originally layer-wound, but were dismantled and rewound in a pancake-fashion, since pancake windings are mechanically sounder than layer windings.

Figure 2 shows the first turn being wound on the coil. The winding mandrel is constructed of 1.11-cm-thick 304 stainless steel. The bottom flange was TIG welded to the bore, and the upper flange was secured to the bore with machine screws after the coils were wound. The insulation on the end flanges is 8.9-mm-thick G-10 plate with radial helium channels 10-mm

\*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

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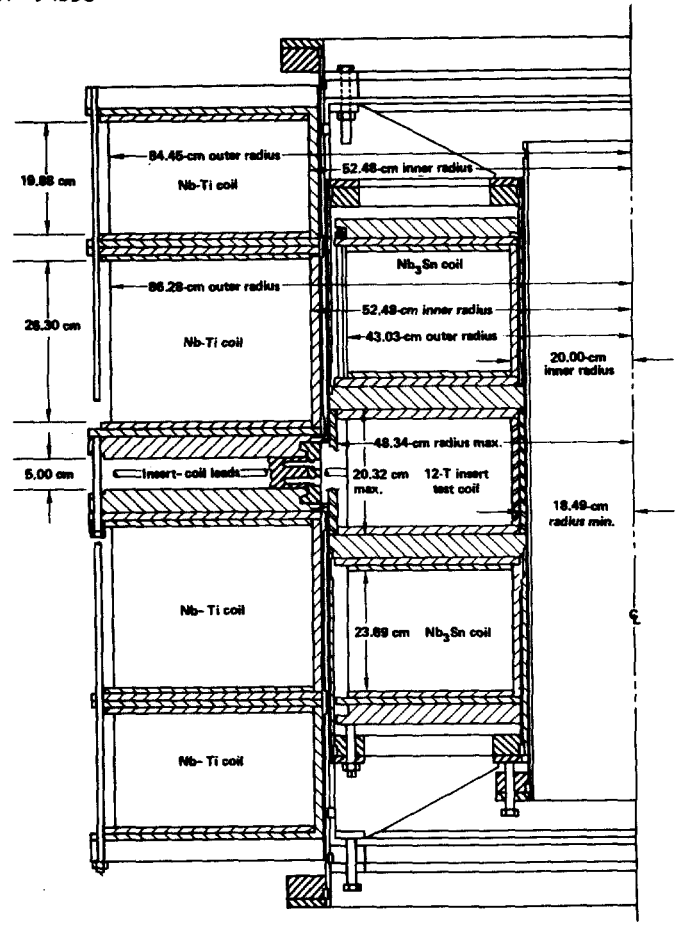


Fig. 1. Half section of HFTF coil system with test insert in position.

Table 1. Parameters of HFTF coils.

	Nb-Ti coils <sup>a</sup>	Nb <sub>3</sub> Sn coils	Tokamak insert
Number of coils	4	2	1
Winding i.o.d. (cm)	105	40	40
Winding o.d. (cm)	170/172.6	91	93.2
Winding axial length (cm)	19.9/26.25	24.25	16.32
Operating current (A)	1,100	5,000	10,000 to 15,000
Current density in winding (A/cm <sup>2</sup> )	3,200	3,080	2,000
Maximum field at conductor (T)	7.5	12	12
Conductor size (mm)	2.5 x 10.0	11.1 x 11.4	---
Ratio Cu/superconductor	4.3/1	5.7/1	---
Heat transfer (W/cm <sup>2</sup> )	0.2	0.35	---
I <sub>c</sub> at maximum field (A)	2,000	~7,500	---

<sup>a</sup>The Nb-Ti coils are separated 5 cm on the center line to permit leads and cryogenic connections to be brought out radially from the coil being tested.

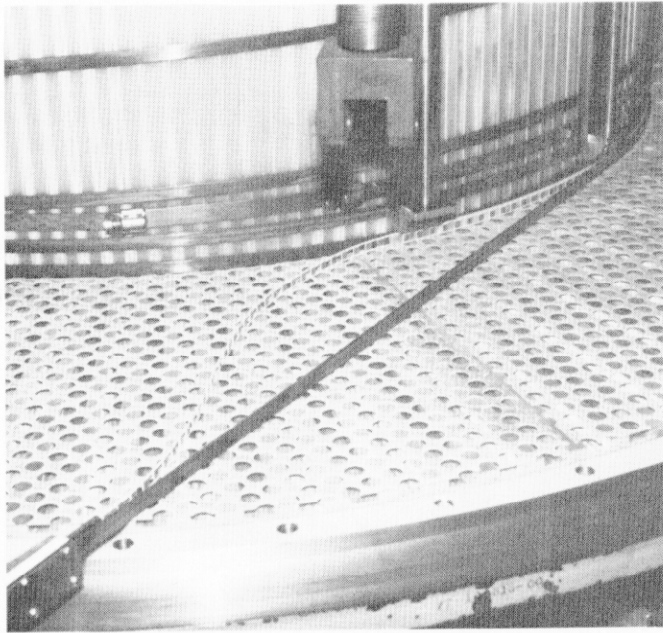


Fig. 2. The first turn.

wide x 5.5-mm deep, covered by 0.89-mm-thick perforated G-10 sheet (interpancake insulation). The insulation on the bore of the winding mandrel is 2.4-mm-thick G-10 sheet with 8.6-mm-wide x 1.6-mm-deep helium channels. The interturn insulation is guided automatically into place on the windings.

The transition joggle on the inner diameter, shown in Fig. 3, was produced with the hydraulic forming tool shown in Fig. 4. The S-shaped blades of the forming tool were contoured in such a way that the joggle produced would conform to the premanufactured G-10 ramps. The transition length was approximately 25 cm, with a maximum bending strain of 1%. The transitions on the outer diameter were also made with this tool.

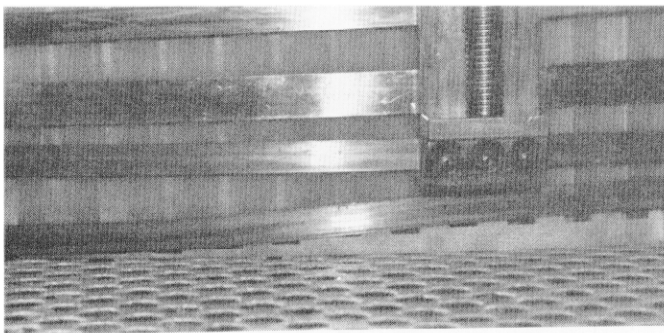


Fig. 3. Transition joggle on the inner diameter.

The fabrication line, shown in Fig. 5, was designed and built to produce the interturn insulation from G-10 strip, 0.89-mm thick, 9.5-mm wide, and 1.2-m long. The material we received was sheared from large sheets, and the resulting variation in widths could not be tolerated. The first step in the fabrication process, therefore, was to grind the strip to the proper width, using a 2.5-cm-diam diamond wheel powered by a router motor rotating at about 20,000 rpm. Then, a 1.8-mm-wide, 0.3-mm-deep step was ground into each edge of both faces of the strip. The grinding

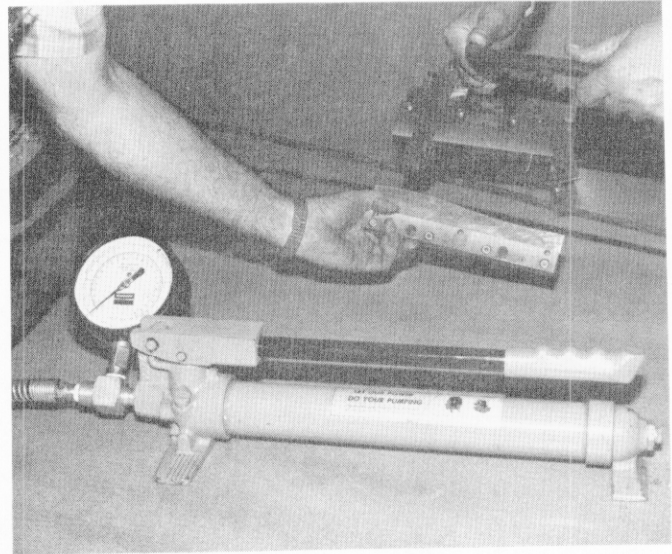


Fig. 4. Tooling for forming the transition joggle.



Fig. 5. Interturn insulation fabrication line.

was done with two pairs of 2.5-cm-diam diamond wheels, one pair for each face, driven by router motors. The grinding stations were enclosed in lucite boxes, and a combination vacuum-air stream system was used to collect the rather copious amount of dust produced. The strip was fed through the grinding stations with drive rollers powered by a dc motor. The third step in the fabrication was a punching operation, in which approximately 50% of the full thickness portion of the strip was removed. A 3-ton air-operated toggle press was used to drive a group of three 6.5-mm square punches. The strip was fed through the punch press with an air-operated hitch-feed mechanism controlled by an air logic system.

Following the punching, the strips were inspected, taped together with Mylar<sup>+</sup> tape, and spooled. A Mylar interleave was used during spooling to prevent snagging of the insulation.

The tensioner was designed and built at LLNL. The conductor was supplied to the winding table through drive rollers mounted on a sliding carriage to which a hanging weight was attached. The drive

rollers were powered by a dc motor. With the drive rollers firmly clamped to the conductor, the hanging weight applied tension on the conductor. A mechanical link to the motor controller increased or decreased the motor's speed as required during winding, thereby maintaining tension on the moving conductor. The nominal winding tension was 100 lbs; during winding, this was maintained to  $\pm 25$  lbs.

All joints in the coils were made by cold-pressure welding, using equipment purchased from Kelsey-Hayes. This process, which was investigated several years ago,<sup>3</sup> has been found to be quite satisfactory. Figure 6 shows a joint being made on the outer diameter.

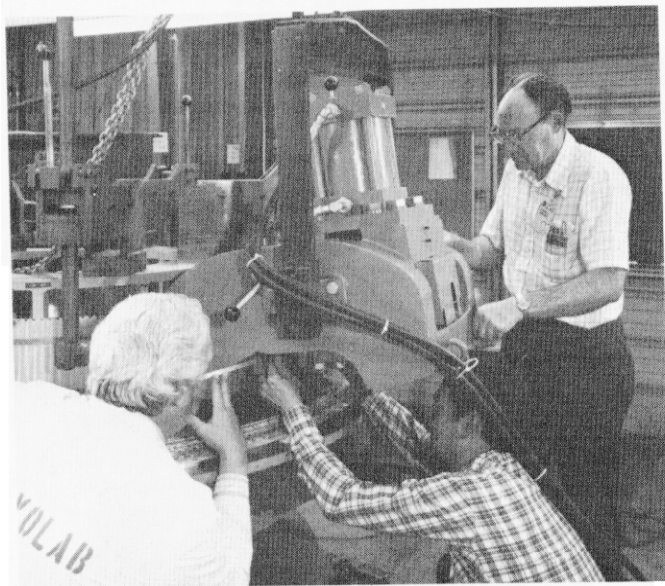


Fig. 6. Making a joint on the outer diameter.

A joggle is made in the conductor on the lower level, approximately  $90^\circ$  away from the weld position. During this operation, radial clamps are used to maintain tension on the windings. The conductors are cut to the proper length, and the cold welder is positioned just above the pancake. The ends of the conductor are inserted into the jaws of the machine and are given a minimum of five pressure applications, which causes the turn to be shortened by approximately 1.3 cm. After the flash is removed and the conductor is dressed down to its original dimensions, the conductor is slipped into place on the pancake and tensioned by driving G-10 strips inside the outer turn.

Each pancake was visually checked to make sure that it was free of any foreign material, dents in the conductor, etc. A set of six axial clamps were used to hold the windings in place. The resistance of the turns in the pancake was checked to make sure that there were no turn-turn shorts, and the height of each pancake was measured to determine the flatness and buildup. The flatness was typically  $\pm 0.7$  mm and the axial buildup was on the order of 0.08 mm/pancake.

After all the pancakes were wound, the top insulation plates and stainless-steel flange were installed. A hydraulically powered cylinder and screw jacks under the axial clamps were used to press on the end flange, with about a 6000-lb total load while it was being fastened in place.

After the terminations were installed, the windings were checked out with a dc hipotter and found to be able to withstand approximately 9 kV to ground. Voltage taps were soldered to the outer turns, near each transition joggle, to allow the voltage on pairs of pancakes to be measured during testing. The outer diameter of the coils was built up with laminate of G-10 strip and interturn insulation to prevent the outer conductors from shearing the interpancake insulation sheets. These were held in place with stainless steel bands.

### Coil Installation

The set of background coils assembled on its cryostat is shown in Fig. 7. The upper and lower pairs

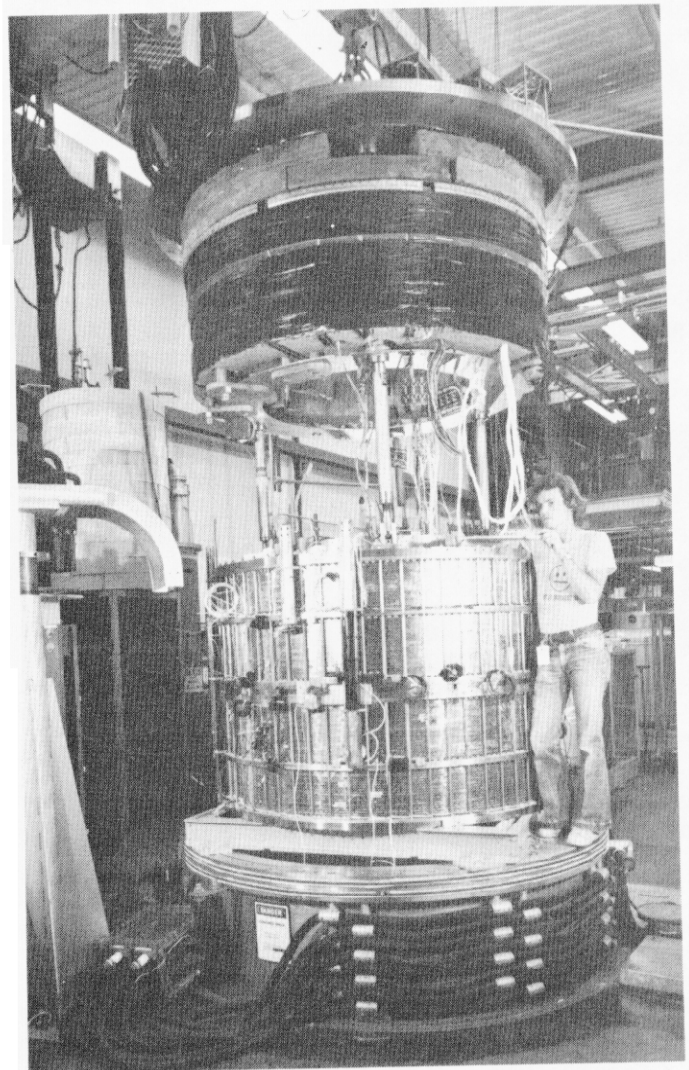


Fig. 7. HFTF background coils.

of coils are structurally distinct. As Fig. 1 shows, each pair has 3.5-cm-thick end flanges, top and bottom. The center flanges are each welded to a core tube. A ring with jack screws is used to compress the coils near the inner diameter; on the outer diameter, a series of tension rods are used to compress the coils. The two pairs of coils are connected to each other by a series of bolts on the outer diameter and vee-type clamps on the inner diameter. The clamps are loaded from the outer diameter with a series of

drawbars. The coils are suspended from the top flange with 304 stainless steel tubes, with an eye-bolt/clevis arrangement on the coil stack and a ball joint on the top flange. A 140-ton truck crane outside the laboratory building, with slings passing through hatch openings in the roof, was used to lower the coil set into the cryostat.

A plug constructed of HD-1623 rigid polystyrene boards from the Dow Chemical Company was installed in the magnet bore to reduce the liquid-helium inventory in the cryostat. Tests performed in our laboratory showed that this material could be cycled to liquid-helium temperature without excessive fracturing and had a very low tendency to soak up liquid helium.

### Coil Testing

Two power-supply systems are used to energize the coils. The two center coils are connected in series to one power-supply system, and the two end coils are connected in series to the other. With this arrangement, the field will remain symmetrical about the mid-plane and prevent the inner Nb<sub>3</sub>Sn and insert coils from being subjected to an undesirable loading.

Each power-supply system consists of a 2000-A, 24-V power supply, with a free-wheeling diode on the output terminals, a circuit breaker, and a protection resistor. The protection resistor is a serpentine arrangement of stainless-steel tubes immersed in a water bath that cools the tubes by natural convection. The center of each resistor is grounded through a 1 K resistor. The pair of larger coils has a 0.8 protection resistor, while the smaller pair has a 0.54 protection resistor. These values were chosen on the basis of calculations using the computer code QUENCH.

In each of the two coil sets, a normal zone is detected with a four-arm bridge circuit in which the upper and lower coils form one side of the bridge and a resistor network forms the other side. The bridge is balanced while charging the coils at low currents, thus nulling out inductive voltages. A bridge imbalance indicates a normal zone in one of the coils. A quench detector constantly monitors the bridge output; should the signal exceed a given level (trip level) for a certain length of time, the circuit breakers are tripped and the coils discharged through the protection resistors. The trip level can be varied from 50 mV to 10 V and the time delay can be set from 10 msec to 1 sec.

The data acquisition and analysis system is based on a Mod Comp minicomputer, which has a 64K word memory and 104 A/D channels. Of these channels, 48 have Preston Model 8300 XWB-A input amplifiers that can operate at 1000-V common-mode voltage. This allows coil voltages to be measured while the coils are being

discharged through the protection resistors. The remaining 56 channels are equipped with relays which open slightly before the circuit breakers and thus protect the computer and other instrumentation.

Data taking can be done in one of three modes: normal, adaptive, or burst. In the normal mode, the sample rate is typically 1 to 10 Hz, with a 50 Hz maximum. The adaptive mode has up to 20 triggers and allows pretrigger information to be obtained. In this mode the maximum sample rate is 50 Hz. The burst mode is used with heater pulse tests. It is limited to 20 channels and has a maximum sample rate of 330 Hz. A pushbutton on the control console simultaneously starts the data taking and fires the heater chassis.

The data is initially stored on disk and is demultiplexed to a nine-track tape automatically when the disk partition is filled. Header information, including date, time, test identification, transducer code, sample rate, etc., are also written to tape, which eases the task of subsequent data manipulation. An extensive software program GPDAP<sup>4</sup> gives us the in-house capability to analyze and plot the data.

The first part of the coil testing program, to energize the center pair of coils to 600 A, with the end coils open-circuited, was underway when we encountered difficulties with our helium recovery system and were forced to curtail testing temporarily. When the helium system is operational, we will resume testing the center coils. Then, we will test the end coils to 600 A, with the center coils open-circuited. Finally, we will test the full set to 1200 A, which will produce a peak field of 8 T. At currents of 800 A and above, we will drive the conductor normal with attached heaters to check the stability of these coils.

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